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Transport mechanisms in low-resistance ohmic contacts to *p*-InP formed by rapid thermal annealing

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Thermionic emission across a very small effective Schottky barrier (0–0.2 eV) are reported as being the dominant transport process mechanism in very low-resistance ohmic contacts for conventional AuZn(Ni) metallization systems to *p*-InP formed by rapid thermal annealing. The barrier modulation process is related to interdiffusion and compound formation between the metal elements and the InP. The onset of low specific contact resistance is characterized by a change in the dominant transport mechanism; from predominantly a combination of thermionic emission and field emission to purely thermionic emission.

Low resistance and reliable ohmic contacts to *p*-InP/InGaAs are needed for maximum performance of both electronic and optoelectronic devices including junction field effect transistors (JFETs) and *p-i-n* photodiodes. Simple, but yet not optimized metallization schemes have been developed,^{1,2} which for the most part employ Au-group II (Be, Mg, Zn) alloys and diffusion barriers such as Cr and TiW.^{3,4} Pt/Ti layers have also been investigated and found applicable as low-resistance nonalloyed ohmic contacts to *p*-In_{0.53}Ga_{0.47}As.⁵ For the transport mechanism of carriers across the metal-semiconductor interface, according to Chu *et al.*,⁵ the complicated interfacial structure of an alloyed ohmic contact can be split into a number of different interfacial segments, in which the simple band theory approach is valid. Thus, transport of carriers across the interface can occur in parallel modes determined mainly by the Schottky barrier height of the individual interfacial segments and the local doping density of the semiconductor beneath these interfacial segments. From these assumptions Chu *et al.*⁵ formulated a phenomenological theory based on a linear combination of the thermionic emission transport mechanism and the field emission (tunneling) transport mechanism to explain the temperature dependence of Pt/Ti ohmic contacts to *p*-InGaAs.⁴ In this letter we discuss the dominant transport mechanism in alloyed AuZn(Ni) ohmic contacts to single crystalline *p*⁺-InP (Zn; $5 \times 10^{18} \text{ cm}^{-3}$).

The ohmic contact dot areas were wet etched through a sputter deposition SiO₂ layer, using standard optical lithography for definition of the dots, followed by vacuum evaporation or rf sputtering for metal layer definition. The metal layers investigated were single AuZn (1000 Å), AuZn/Au (1000/200 Å) and Au/Ni/AuZn (500/250/1000 Å) layers. Large-area AuZn backside contacts were also deposited in order to ensure a good backside contact. The measurement of the specific contact resistance was done using the Cox and Strack technique⁶ for the contact dots circular in shape and of different areas. The annealing was performed in a Heatpulse 410 rapid thermal annealing (RTA) system keeping the annealing time constant at 20 s. AuCr probing pads in contact with the dots were patterned on top of the SiO₂ layer after the annealing in order not to disturb the dots during *I-V*-(*T*) measurements.

The specific contact resistance as a function of the annealing temperature is shown in Fig. 1. The lowest value of r_c , $7 \times 10^{-6} \Omega \text{ cm}^2$, was obtained for a single AuZn layer at an annealing temperature of 440 °C. Adding 200 Å of Au in between the AuZn layer and *p*-InP, increases the minimum value of r_c two times, but also lowers the onset temperature of low specific contact resistance as compared to the single AuZn layer case. Adding 250 Å of Ni alters the r_c characteristic as compared to both the single AuZn layer and the AuZn/Au layer case. The minimum specific contact resistance of $2.7 \times 10^{-5} \Omega \text{ cm}^2$ occurs at a temperature of 430 °C, but then increases to a level of about $10^{-3} \Omega \text{ cm}^2$ above 430 °C. Also, the addition of Ni lowers the onset of low specific contact resistance even further.

According to Chu *et al.*,⁵ can be calculated as

$$r_{c,th} = \frac{k}{j_1(f_1)eT} \exp\left(\frac{e\phi_{b,eff}}{kT}\right) \quad (1)$$

for thermionic emission, where k is the Boltzmann constant, e is the elementary charge, T is the absolute temperature in Kelvin and $\phi_{b,eff}$ is the effective Schottky barrier. Similarly, for field emission, r_c can be calculated as⁵

$$r_{c,tu} = \frac{\sqrt{N}}{j_2(f_2)C_1C_2} \exp\left(\frac{C_2\phi_{tu}}{\sqrt{N}}\right), \quad (2)$$

where N is the doping concentration of the semiconductor, C_1 and C_2 are constants, and ϕ_{tu} is the tunneling barrier. $j_1(f_1)$ and $j_2(f_2)$ are microstructural factors describing the thermionic and field emission assisted transport, respectively. For a perfect chemically abrupt metal-semiconductor interface, for example, $j_1(f_1) = A^*$; the Richardson constant. From Eq. (1), if thermionic emission over an effective Schottky barrier is the dominant transport mechanism a plot of $r_c T$ in a logarithmic scale versus $1000/T$ should then be linear. If, however, a deviation from linearity is present, this strongly suggests that a temperature independent transport mechanism, like field emission, is contributing as well.

For information of the dominant transport mechanism across the metal-semiconductor interface, we therefore measured the specific contact resistance as a function of the ambient temperature T . The results of the experiment are shown in Fig. 2 for the AuZn/Au case. The ambient tem-

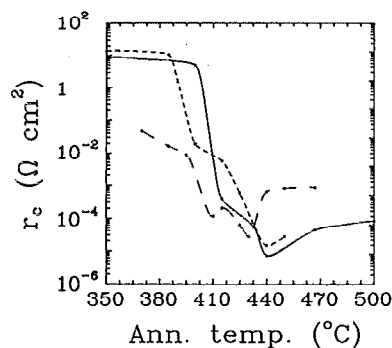


FIG. 1. Specific contact resistance vs annealing temperature. Solid line, AuZn/ p^+ -InP; dotted line, AuZn/Au/ p^+ -InP; dashed line, Au/Ni/AuZn/ p^+ -InP.

perature was only varied from room temperature to a temperature of about 175 $^\circ\text{C}$ in order to avoid any thermally induced degradation of the contact. As can be seen from Fig. 2, increasing the annealing temperature for the ohmic contact from 350 to 440 $^\circ\text{C}$ causes a decrease in the temperature dependence of $r_c T$. Although not clear from Fig. 2, there is a deviation from linearity from the annealing temperature of 350 and 400 $^\circ\text{C}$, but for annealing temperatures above 400 $^\circ\text{C}$, the linearity is quite good. Thus, from Fig. 2, thermionic emission across an effective Schottky barrier, calculated from the slope of the lines, is dominant for annealing temperatures above 400 $^\circ\text{C}$, while field emission contributes to the overall conduction mechanism for annealing temperatures below 400 $^\circ\text{C}$.

In Fig. 3 the effective Schottky barrier $\phi_{b,\text{eff}}$ obtained from the linearity of the lines in Fig. 2 is shown. Similar measurements for the AuZn single layer case and the Au/Ni/AuZn case are also included in Fig. 3. For nonlinearities in the $r_c T$ vs $1000/T$ curves, indicating that a combi-

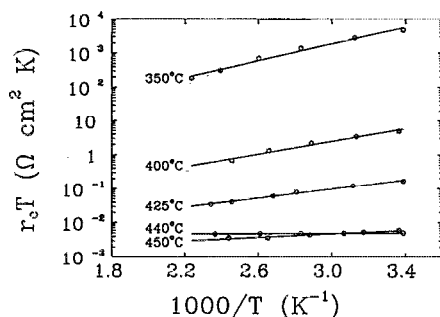


FIG. 2. Temperature dependence of specific contact for AuZn/Au/ p^+ -InP.

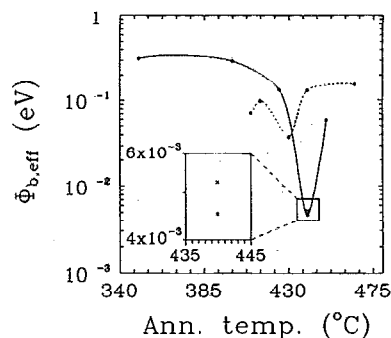


FIG. 3. The effective Schottky barrier ($\phi_{b,\text{eff}}$) vs annealing temperature as obtained from the $r_c T$ vs $1000/T$ plots of Fig. 2; solid line, AuZn/Au/ p^+ -InP; dotted line, Au/Ni/AuZn/ p^+ -InP. Magnification shows $\phi_{b,\text{eff}}$ for AuZn/ p^+ -InP (x) and AuZn/Au/ p^+ -InP (*) at their minimum value at 440 $^\circ\text{C}$. value

nation of thermionic emission and field emission are active, $\phi_{b,\text{eff}}$ has been determined from the temperature dependence of the ohmic contacts at high ambient temperatures (> 100 $^\circ\text{C}$). From Fig. 3 low specific contact resistance for alloyed AuZn(Ni) metallizations is associated with a reduction of $\phi_{b,\text{eff}}$ to values very close to 0 eV, and onset of pure thermionic emission across the barrier. Also, from the insert of Fig. 3, the measured barrier height at 440 $^\circ\text{C}$ for the single AuZn layer and the AuZn/Au layer does not differ significantly. From Refs. 1-4 low specific contact resistance is also associated with interdiffusion and compound formation between the metals and the semiconductor starting above 400 $^\circ\text{C}$ annealing for the single AuZn layer case. Thus, Schottky barrier lowering and compound formation between the metals and the InP are closely connected.

In conclusion, by applying simple conventional band theory to an alloyed ohmic contact, it has been shown that the dominant transport mechanism in low-resistance alloyed AuZn-based metallizations to p -InP is thermionic emission across a small effective Schottky barrier $\phi_{b,\text{eff}}$ on the order of 0-0.2 eV. The reduction in $\phi_{b,\text{eff}}$ is associated with interdiffusion of elements and subsequent compound formations adjacent to the InP surface.

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